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INCREMENTAL ARCHITECTURES FOR A PERMANENT HUMAN LUNAR OUTPOST WITH FOCUS ON ISRU TECHNOLOGIES

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Long-term strategic plans for future human space exploration are based on the idea of following an evolutionary path, as this is fundamental to reduce risks and costs associated to deep space missions, as well as to allow testing and validation of critical technologies required for ultimate goals, such as human Mars missions. In this context, in addition to its utility as a precursor for Mars expeditions, extended lunar exploration is of interest in itself, especially since the surface of the Moon is very rich in resources, but it has not so much been explored in-situ. Extended lunar operations may eventually require the establishment of a human lunar outpost. Determining what technologies will be required to accomplish this goal is the motivation for our research. The present paper outlines the conceptual design of a permanent human Moon outpost located at the lunar south pole, defining the main requirements and presenting the arisen system architecture highlighting the incremental steps needed to achieve full operational capability. Particular attention has been given to the design of the base main elements, especially incorporating In-Situ Resource Utilization (ISRU) technologies as a paramount brick of the overall design process. Estimates regard the crew size and the related life support systems, and chiefly the ISRU plants production rate needed to allow the primary lunar base self-support. Moreover, ISRU is considered not only as an enabling factor for affordable human long-term presence on the Moon, but also as an opportunity to provide spacecraft travelling to the Red Planet with propellant, thus reducing their launch mass: calculations are made considering refueling at the Earth-Moon libration point L1, where liquid oxygen tanks would be delivered from the lunar surface. Oxygen extraction through ilmenite reduction is the main technology considered for dimensioning ISRU plants. Another precious resource could be found in sunless cold trap craters at the Moon's south polar region. However, ground truth for the presence of water ice inside these traps has never been provided. For this reason, the scenario described in this paper envisages robotic survey missions: initially, they will be tele-operated from the Earth, and later on from a lunar lander in sortie missions, or even from the outpost itself. In this way, alongside the ongoing production of oxygen through well-mastered technologies, research activities could flourish to improve and innovate the lunar outpost endeavor.

I. INTRODUCTION

Human exploration of the Moon and utilization of its potential mineral resources as an incremental step towards Mars is here considered in line with future space exploration scenarios[1], also accounting for enabling technologies identification. A permanent base for scientific activities and technology development and validation purposes is envisioned as the ideal starting point for Solar System manned exploration. This decision follows a careful evaluation of possible missions based on NASA criteria[2], which lead us to conclude that a Moon Outpost mission is favorable with respect to standard missions under almost every aspect, except schedule risk and life cycle cost, due to the large number of campaigns needed to achieve the goal.

Main Objectives

Based on a detailed stakeholder analysis with focus on Need Intensity and Source Importance[3] of the various entities, the increase of international public-private partnerships with a significant contribution from private companies, as well as the education and engagement of the public emerge as primary general objectives of the mission. On a more technical level, to develop radiation protection capabilities, ISRU capabilities and life support technologies for exploration are the main drivers. ISRU capabilities are hereby further analyzed with the objective of sustaining a permanent lunar base by 2029[4] and future missions to Mars, obtaining requirements along with the definition of several architectures answering the broad objectives identified above. Both current technology and plausible development are here considered, including the possibility of cold traps exploitation. The Apollo and Luna missions brought back over 382 kg of lunar samples, but since most of them were collected from the equatorial regions which are unrepresentative of the lunar surface, more sampling needs to be performed, especially in polar regions, before actually considering cold traps. Data on those regions are only known from remote sensing surveys of satellites orbited around the Moon by space-faring nations, from which the presence of water ice in permanently shadowed craters near the poles has long been suggested[5]. Water is thought to be enclosed in these cold traps where the temperature is below 40 K due to their particular geometry. The removal of water from regolith pores is a physical process requiring far less energy than oxygen extraction through hydrogen reduction of lunar ilmenite, which is the most up-to-date technology. Of course, a campaign to locate and validate accessible water ice resources must be carried out beforehand: were this campaign successful, then an affordable human long-term presence on the Moon would be enabled.

Recent studies have suggested that cold trap water ice could be present in Craters Cabeus and Shackleton[6], but also in Aitken basin[7]. Icy materials in smalls craters appear as small grains (approximately less or equal than 10 cm in size) mixed with regolith, or as a thin coating of ice on rock. These measurements are in urgent need of verification: in fact, the source of hydrogen may be due to accumulation of solar wind hydrogen, and not to the presence of water[8]. However, accessing cold traps, identifying the presence of ice, and exploiting them are activities that pose major technical challenges, and are therefore beyond the scope of near-term missions.

ISRU Importance

ISRU carries many implications on a permanent human lunar settlement[9,10,11]. Several are the benefits that can be traced back to the incorporation of ISRU in the outpost design from the beginning, i.e. involving the phases of outpost deployment until lunar base growth and self-sufficiency[12,13]. ISRU for water and oxygen production can be used for a complete closure in life support systems, for the regeneration of fuel cell consumables, and for the production of propellant for robotic and human vehicles. Moreover, water can be used for radiation protection and for thermal energy storage. Finally, regolith processing can lead to improvements in site preparation, structures construction and spares production, in-situ repair and reuse, thermal energy storage, power generation through He-3, and radiation protection. All the mentioned aspects result in two important advantages coming from ISRU: mission flexibility due to use of common modular hardware and consumables, and reduction in launch costs, since the more the elements produced in-situ, the lower the mass to launch.

II. OUTPOST LOCATION

A trade-off analysis[14] on potential locations where the outpost can be placed identifies two important regions, i.e. the equator and the south pole. However, even though that on the Equator there could be more resources (e.g. He-3) and other benefits could be achieved, the lunar south pole is considered due to the need of cold traps proximity.

The south polar region has two factors that greatly favor human exploration: nearly constant sunlight - which allows for incremental buildup, easier thermal control, and power generation - and the likelihood of water. Moreover, low ΔVs are required to reach the south pole and launch windows are more frequent. Finally, communication is much simpler and continuous at the south pole with respect to the equator.

Thus, the lunar south pole appears to be a more suitable location for a permanent outpost. The precise location must then be sought near the south pole, and two main sites are here considered.

Mount Malapert

Mount Malapert, the biggest mountain near the south pole (the upper circle in Figure 1), is on the visible side of the Moon. Long periods of sunlight and a continuous communication link with the Earth are highly advantageous. Moreover, it is located near areas that may contain water ice, as it has a permanently shadowed crater at its base. The mountain's base is also well suited for the operation of telescopes, particularly radio telescopes that can be shielded from the radio noise of the Earth, and infrared telescopes that are placed on the low-temperature floors of craters.

However, the slopes around Mount Malapert are quite high and might be an obstacle for a safe landing near the outpost site.

Shackleton Crater

Another possible location on the south pole could be on the rim of Shackleton crater, which is located at the geographic south pole (the lower circle in Figure 1). This spot receives sunlight around 80% of the lunar day and has similar characteristics to the ones of the Mount Malapert. Interpretations of data indicate that the rim of Shackleton Crater is visible from the summit of the Mount Malapert, thus, the mountain could become the center of communications thanks to its direct link to Earth. The habitat can be placed in a highly lighted zone together with a power generation facility, while a relatively flat landing zone is available a few kilometers away.

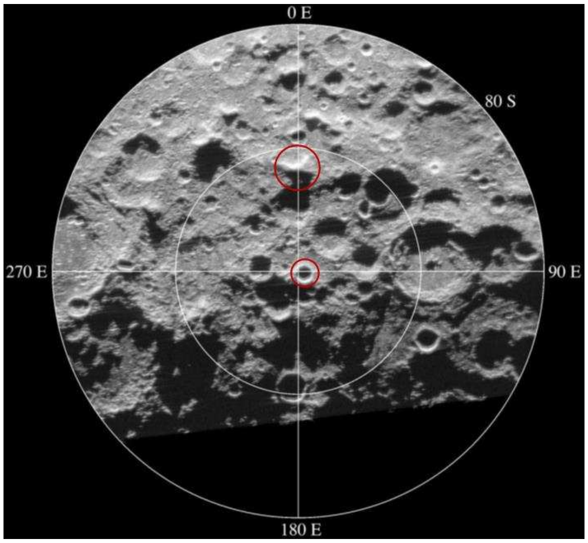


Fig. 1: Lunar south pole. The highlighted spots are Mount Malapert and Shackleton Crater.

Location Trade-off

A set of Figures of Merit (FoM) can be identified to better choose the location of the outpost. The selected location must allow for continuous communication with Earth, in order to guarantee a permanent link between astronauts and Mission Control, and must be in light as long as possible, to exploit at maximum solar arrays as a primary source of power. Moreover, a safe landing site must be present near the base, to allow a fast reentry in case of an emergency. Finally, the outpost should be near a cold-trap crater, in order to perform experiments and ISRU. Ground and soil configuration could be used to partially shield the outpost from radiation, but an assessment must be performed in-situ to evaluate soil properties and stability.

As it can be seen in Table 1, even though Mount Malapert seems to be a suitable location thanks to its direct link possibility and almost permanent lighting, it is penalized by the upper-ground position, which implies steep slopes that must be faced to reach a safe landing site and the cold trap at the base of the mount. On the other hand, positioning the outpost on the rim of Shackleton Crater allows ease of access to both landing site and cold traps, with a reasonable decrease in lighting time and the necessity of a repeater on the top of Mount Malapert to guarantee continuous communications with Earth.

FoM	Weight	MM	SC
Continuous Comm	0.25	5	3
Lighting	0.30	5	4
Landing Site	0.25	2	5
Cold-traps Access	0.20	3	5
Total Score		3.85	4.20

Table 1: Trade-off analysis.

Illumination Analysis

Using a virtual reality facility[15] and high-resolution (230 m/pixel) digital elevation models of the site of interest, real time shadowing maps can be produced fixing a position for the Sun. Overlaying the single frames obtained during a lunar day, it is possible to build an illumination map of the area of interest. Using this map - and future ones with higher resolutions - it is possible to evaluate the positioning of various lunar surface assets or components, such as solar panels and lunar greenhouse. In Figure 2, the south pole is represented as a blue circle and the red lines determine the most lighted areas. The south pole itself is not considered, as it creates a singularity while meshing that made us discard the results obtained within a range from it.

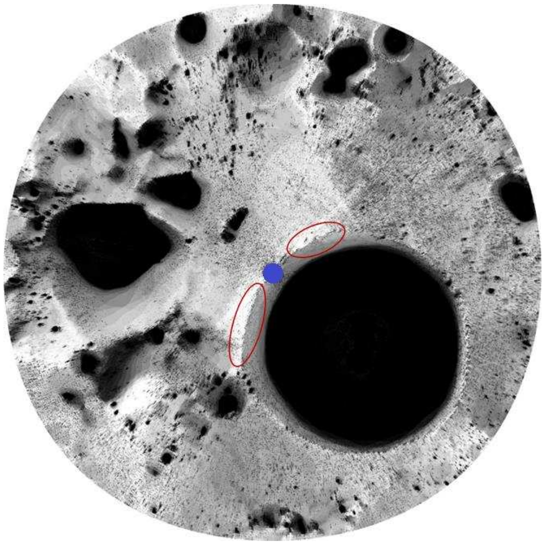


Fig. 2: Shackleton Crater and surroundings illumination map.

III. OUTPOST ARCHITECTURE

Once the location has been identified, it is possible to define the elements composing the outpost with a high-level functional analysis. The final layout will include:

- A surface habitat with airlocks for Extra Vehicular Activities (EVAs)
- A lunar science module
- An ISRU plant with relative utilities (i.e. power plant and rovers)
- Manned and unmanned rovers for exploration, maintenance, and outpost growth
- A spaceport with ascent/descent vehicles
- A greenhouse with storage module
- A lunar communication terminal
- A power plant to sustain everything but ISRU activities

Crew estimates

In order to perform all the tasks imposed by the size and characterization of the outpost, the crew must be sized accordingly. To perform EVAs without major constraints and to have support by at least two crewmembers while others are outside, a minimum of four astronauts shall be assumed for the crew. Moreover, considering return vehicles, the crew shall not exceed their capacity (i.e. six for an Orion capsule). To determine precisely the number of crewmembers, psychological considerations are needed[16]. These include, but are not limited to, social density (volume available for each crewmember), confinement (crew size/expected mission duration), physical environment (freedom of movement, subjective perception of habitable volume, atmosphere, time outside the outpost), and work/rest ratio (workload, rest and leisure time, tasks variations). Perceived relevance of the task strongly influences crew motivation, morale, and relationship with ground. Thus, the total duration of the mission has a fundamental role: based on ISS missions, we assumed a minimum stay of 180 days. The maximum permanence on lunar surface is fixed at 240 to 360 days, mainly due to the little sensitivity of volume to mission duration for stays of more than six months, and to the fact that no microgravity implies lower physical deconditioning (however, effects of low gravity have not been assessed yet). Once the duration of the mission is established, a more detailed task analysis is performed.

Task analysis

This study has been performed trying to focus on activities to be done and their workloads, frequency and main stressors. In general, all the activities can be performed by one or more among crew on Intra Vehicular Activity (IVA), crew on EVA (both with and without rovers), unmanned teleoperated rovers, unmanned autonomous rovers, mission control and ground support. Our analysis led to the identification of cross-training tasks (i.e. tasks that can be performed by more crewmembers since they are not extremely specific) and consequently, tasks for only one astronaut can be identified, confirming a number of crewmembers between four and six, with six being the most likely. Moreover, considering long-range manned rovers operations (two astronauts on EVA, plus one for support) and frequency of these missions, the final number of crewmembers adopted is six.

The pressurized volume needed is usually 25 m^3 per person. However, taking into account that a low-gravity environment means that only part of the module can be accessed, but - for psychological reasons - ceilings should be high enough, the estimates for pressurized volume are around 100 m^3 per person. Thus, a total of 600 m^3 of pressurized volume is needed.

IV. ISRU REQUIREMENTS

To identify the main requirements for an ISRU plant, the technology to be used must be identified. Ilmenite reduction is here considered leaving some room for exploring new ISRU technologies, namely oxygen extraction from cold traps. Although ilmenite reduction applies particularly to titanium-rich regolith, more typical in lunar maria in near-equatorial regions, it is preferred since it has a higher Technology Readiness Level (TRL) than other solutions. Thus, we suggest using it for the beginning while trying to develop and test other, more efficient, techniques.

Lunar regolith is the most likely primary feedstock from which we can extract useful resources. Regolith is made up of tiny particles that mainly contain minerals such as plagioclase, pyroxene, olivine, ilmenite ($FeTiO_3$), and spinel. Producing oxygen from regolith through ilmenite reduction is one of the likely initial applications of ISRU. The reaction, which needs heating the regolith up to 1050°C, has water as primary product (Equation 1), which may be electrolyzed to obtain oxygen and hydrogen (Equation 2), with the hydrogen being re-used in further reduction.

$$FeTiO_3 + H_2 + heat \rightarrow Fe + TiO_2 + H_2O \quad [1]$$

$$H_2O \rightarrow H_2 + 0.5\ O_2 \quad [2]$$

We have defined several phases (i.e. campaigns) for developing the ISRU necessary for lunar base self-sustainment, from robotic teleoperated rovers to big plants processing large quantities of regolith. According to this incremental scenario, estimates for yearly ISRU requirements are performed. Oxygen for both IVA and EVA (frequency of one EVA of three crewmembers every 10 days) support is the primary function of ISRU plants, followed by production of propellant for lunar ascent and reentry, and finally by production of propellant for Mars missions.

IVA and EVA Support

Considering a year worth of oxygen, and potable and non-potable water needs for six crewmembers, a huge mass of oxygen should be produced on lunar surface. Modern Environmental Control and Life Support Systems (ECLSS) are capable of high percentages of regeneration, and in the future, they will reach new peaks. A plausible value of 96% regeneration has been considered for this analysis. Results are reported in Table 2. Almost 2.5 mT of oxygen per year shall be produced to support life during lunar outpost operation.

Need	Mass (kg)
IVA breathing O2	1 814.40
IVA potable water	7 603.20
IVA non-potable water	54 864.00
EVA breathing O2	68.04
EVA water	583.20
Total O2 w/ regeneration	2 317.09

Table 2: Oxygen and water needs for different functions.

Reentry Support

Since ISRU plants can produce more than that (up to 20 mT per year according to our analysis), the next step is to consider ascent and reentry vehicles using in-situ produced propellant to cancel the dependence on Earth-brought propellant, thus saving huge amounts of Initial Mass to Low Earth Orbit (IMLEO).

We followed a reverse procedure starting from the final outpost configuration to determine the total mass of oxygen needed. First, we analyzed the reentry trajectory: it consists in a Trans Earth Injection (TEI) maneuver with a ΔV_{TEI}=0.93 km⁄s followed by a direct reentry, which implies no ΔV. The Crew Exploration Vehicle (CEV) and the Service Module (SM) are taken from DRA 5.0 and are supposed to orbit around the Moon waiting for a crew to go back to Earth. With this in mind, the CEV+SM is our payload. Considering a structural index (i.e. the structure's mass over the total mass ratio) of 0.3 in order to account for a high precision control system and a reentry thermal system, the total mass of oxygen needed is 2.11 mT per reentry. This oxygen shall be brought into Low Lunar Orbit (LLO) together with the ascent vehicle that brings the crew. Our payload from lunar surface consists then in the oxygen for the next phase and in the ascent vehicle derived from the Mars Ascent Vehicle of DRA 5.0, which has a 13.20 mT mass. Since ΔV_{LLO}=1.83 km⁄s, the best approach consists in a 2-stage ascent vehicle, with both stages having a 0.15 structural index. It results that 6.57 mT of oxygen are needed to lift the ascent vehicle, the crew, and more propellant into LLO to return to Earth. Assuming that two reentry missions per year are performed, the total oxygen need is obtained (Table 3). It was found that a total of almost 20 mT of oxygen per year are needed to support completely (i.e. IVA, EVA, and reentry) outpost operations: with this production rate, life-cycle costs can be drastically reduced.

Maneuver	LOX Mass (kg)
Lunar surface to LLO	6 570.00
TEI	2 110.00
Total for two reentry/year	17 360.00

Table 3: Liquid Oxygen (LOX) need for Moon-Earth propulsion.

Mars Mission Support

Once the outpost is almost self-sustaining, the next step is to use it to support other missions. Since the final goal is Mars manned exploration, the outpost should be capable of supporting that kind of mission. If we want to use lunar produced propellant to reach Mars, the first thing to understand is where such propellant can be stored and then exchanged with the deep space spacecraft going to the Red Planet. Thorough analyses lead to consideration of the Lagrangian point L1 as a suitable candidate for exchange and storage. A depot in L1[17], in fact, can be maintained in a halo orbit with low station-keeping needs, has a privileged position for Earth communications, and can be reached easily both from Earth and the Moon.

With this system in place, a mission for Mars should be launched in LEO and from there, travel to L1 to rendezvous with tanks previously sent from the lunar surface containing all the oxygen needed for the inbound trip to Mars. At that point, using a gravity assist from Earth, the spacecraft can perform a Trans Mars Injection (TMI). Once it arrives near the target, the spacecraft performs a Mars Orbit Injection (MOI), stabilizing its trajectory around the planet near all the equipment previously sent using electric propulsion to lower the IMLEO of the actual mission and to perform preliminary analysis of what the astronauts will find.

Since all the material not needed for the inbound trip will be sent in a different way, the payload that we have to carry consists of a CEV+SM of 10.6 mT, a Deep Space Habitat of 32.8 mT, and a Contingency Food Canister of 9.8 mT, for a total of almost 55 mT. Once all this arrives in L1, refueling must be performed and then it can leave. A first burn to enter an orbit towards Earth is necessary and then, at perigee, a second burn is necessary to perform the TMI (ΔV_{TMI}=1.51 km⁄s). These burns are performed by a single stage that requires 31.29 mT of oxygen considering a 0.15 structural index. To perform the MOI (ΔV_{MOI}=1.70 km⁄s), a second stage with a higher index (i.e. 0.25) shall be considered since more precision is required, resulting in a total need of 23.08 mT of oxygen.

To furnish the inbound spacecraft with everything it requires, oxygen for ECLSS shall be produced too. Considering a crew of six and an outbound trip of 202 days, a total need of 1.27 mT of oxygen is estimated.

This results in 55.64 mT of oxygen needed for the trip to Mars, which must be transferred to L1 from lunar surface. Since ascent vehicles cannot lift all this mass at once, a subdivision has been adopted. If we consider a maximum of 20 mT of payload per each ascent, with an iterative procedure we can find the mass of the tanks and the actual mass of oxygen per launch. Assuming that tanks have a standard shape and considering ascent vehicle configuration, the optimal tank geometry can be found to minimize structural and insulation masses: more than 19 mT of oxygen can be launched with every ascent vehicle, thus resulting in a total of three ascents to bring to L1 all the oxygen needed for a Mars mission.

To lift 20 mT of payload from the surface to L1, we first have to reach LLO and then move to L1 ($\Delta V_{LLO\text{-}L1}$=0.64 km/s). We opted for a two stage ascent vehicle with a more precise second stage (structural index of 0.25 against 0.15 for the first stage), which results in a total oxygen mass of 13.41 mT per launch. The total amount of oxygen to be produced can be seen in Table 4.

Maneuver or System	LOX Mass (kg)
TMI	31 290.00
MOI	23 080.00
ECLSS	1 270.00
LLO (for 3 ascent mission)	32 520.00
L1 O2 (for 3 ascent mission)	7 710.00
Total (for 1 Mars mission)	95 870.00

Table 4: LOX need for L1-Mars propulsion.

Concluding, if 26 months pass between two consecutive missions[18], we find that a total of almost 45 mT of oxygen per year are needed to support Mars exploration: a significant reduction in number of launches (one launch with an SLS 70 M and one with an SLS 130 versus a total of five launches for DRA 5.0) and IMLEO is obtained. However, with this production rate, new plants must be installed and there is the risk that ilmenite reduction techniques might not be efficient enough for this rate, thus, the presence of water could be a major enabling factor since cold traps plants could be more profitable.

ISRU yield

In this section, we summarize the estimates that have been performed so far, and make some new computations in order to establish a trade-off among the various ISRU techniques available. As usual, we try to exploit the existence of water ice in cold trap craters, and try to determine the threshold values for water content and water extraction efficiency below which it is not convenient to produce oxygen in this way.

Using the estimates done so far, we gather that the ISRU plant production in steady state is divided as follows: 20 mT per year for lunar propulsion and life support, and 44 mT per year for Mars propulsion.

This means that full operational capability is reached when LOX production exceeds 64 mT per year. First, as it will be seen in Section VI, at least one plant producing 20 mT per year of LOX (hydrogen reduction of ilmenite) will be present on the Moon before Mars propellant production starts. This plant is needed to sustain Moon activity and exploration, for example to detect new sources of ISRU (cold traps exploration above all). The optimal solution is to find a process whose efficiency does not depend on the ilmenite content of the feedstock. On the contrary, if no other technique is found to be suitable for lunar oxygen extraction, three new ilmenite reduction plants shall be added to the one already in place.

However, if we suppose that all the remaining 44 mT per year of oxygen could be produced starting from cold traps, then we can make the following considerations. In principle, we can state that a certain mass of water ice is necessary to obtain the target mass of oxygen. This mass is given from the mass of water scaled with the stoichiometric ratio between oxygen and water. The mass of water is obtained from the mass of soil accounting for a certain extraction efficiency (i.e. kg of pure water per kg of water) and a certain water content (i.e. kg of water per kg of soil). This concept is expressed by Equation 3.

$$[kg_{LOX}] = [kg_{soil}] \times \eta_{extraction} \times content_{H2O} \times \frac{MM_{O2}}{MM_{H2O}} \quad [3]$$

For the content, the value observed by LCROSS in 2009 is 5.6 ± 2.9 %, but in-situ verification is compulsory; extraction efficiency takes into account melting and filtering losses; and the stoichiometric ratio is well approximated by 8/9.

According to Equation 3, we obtain the curves in Figure 3, from which we understand that to obtain 44 mT per year of LOX with ilmenite reduction at 2.5 % yield, 1760 mT per year of regolith are needed. In order to be more profitable with cold traps extraction, at least 2.88% water content is needed with extraction efficiency of 1, 3.2% with 0.9, 4.12% with 0.7, and 5.76% with 0.5.

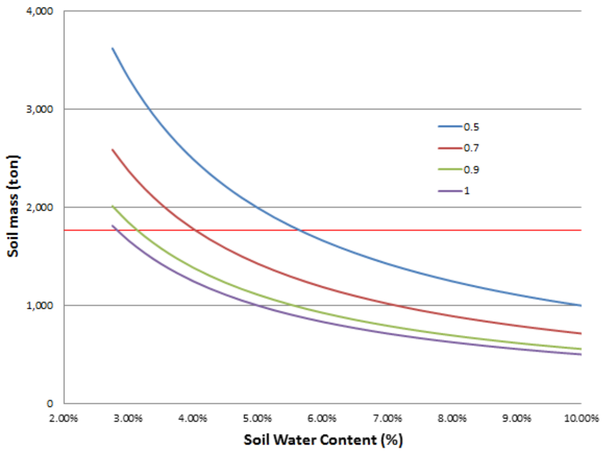


Fig. 3: Mass of soil needed for 44 LOX mT per year production with different extraction efficiencies. The red line is the limit of 1760 mT of soil per year needed with ilmenite reduction.

On the other hand, if we employ a model where fixed costs are considered, as in Figure 4, with an increase in fixed cost for every additional 10 mT per year of produced LOX, then we conclude that cold trap fixed costs decrease with respect to ilmenite reduction, but content multiplied by extraction efficiency must be above a certain value to make cold traps profitable. Otherwise its effect outweighs the benefits from lower fixed costs.

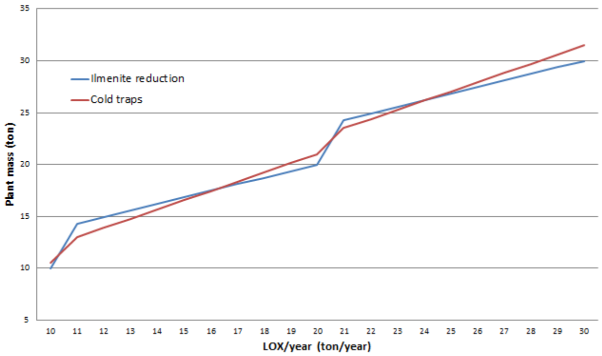


Fig. 4: Plant mass as function of LOX per year production requirements, where fixed costs increase every 10 mT per year. This graph is realized considering an extraction efficiency of 0.9, and a regolith water content of 1.5%.

In general, to collect data and perform preliminary studies on cold traps exploitation, we envision the use of ilmenite reduction plants to melt the icy regolith coming from cold traps using heat losses during the process (cf Section V). That is possible since these plants require temperatures of around 1050 °C, and an ice-soil mixture needs only to be heated to about 50°C. The additional plant elements and masses required can be estimated starting from the assumptions on the heat losses of the main reaction chambers of the ilmenite reduction hardware.

Radiation Shielding

The lunar base architecture previously described accounts for stays lasting six months to one year. Chronic exposure to highly ionizing radiations in the Galactic Cosmic Rays (GCRs) and sporadic acute exposures to Solar Particle Events (SPEs) are serious hazards that can be mitigated in part by radiation shielding. The most obvious solution to shielding can be found in the utilization of lunar regolith, whose supply on the lunar surface is essentially unlimited, and there is of course no need to transport it form Earth. We choose lunar regolith for other reasons as well: it is in fact a great material to provide protection against meteorite impact, and diurnal cycle temperature buffering[19].

While on the Moon, the radiation quantities to consider are approximately half that of deep space, thanks to the presence of the soil: however, the presence of secondary radiation (mostly neutrons coming from radiation interaction with the ground) must not be overlooked. Moreover, preliminary robotic missions may also contribute to measure radiation exposure and absorption, thus better characterizing the environment. Experimental measurements on Apollo samples, synthetic regolith and lunar simulant[20] show that regolith has weighted average charge and atomic weight similar to aluminum and is almost as good as at shielding GCRs, and that its percent dose reduction per unit areal density is approximately half that of polyethylene. The dose reduction as function of depth exhibits the characteristic behavior of ionization energy loss by heavy charged particles. For the lunar soil, approximately 90% of the dose is estimated to result from nucleons for shield layers greater than approximately 20 g/cm^2. For the much higher energetic GCR spectrum, the greatest reduction in the dose takes place in the first 20-30 g/cm^2. In practice, results suggest that 25 g/cm^2 regolith is needed to almost completely attenuate a single beam energy: this means a depth of approximately 15 cm assuming a regolith density of approximately 1.9 g/cm^3 (lunar regolith range of densities is 0.8-2.15 g/cm^3). On the other hand, an SPE - whose probability in a 6-month rotation lies in the range 1-10% - consists mainly of energetic protons of very high intensities. Considerations of the energy spectrum of the events lead to the conclusion that 5 cm of regolith packed at a density of 1.9 g/cm^3 can stop 100 MeV protons, and 18 cm would be needed for 200 MeV protons instead. For heavy shielding (i.e. more than 20 g/cm^2), GCR dominates over SPEs and further addition of shielding only provides marginal reductions.

Albeit many investigators provide point estimates of the doses due to GCR or SPE for specific locations in space, the current NASA trend is to utilize the 95th percentile Confidence Interval (CI) rather than the point estimate for dose. In cases where the 95% CI has been modeled, the dose is typically 3 to 4 times the point estimate (multiplication by 3.5 is generally used)[21]. Considering then a radiation scenario of 6-month stay plus one major SPE (February 1956 SPE is taken as a reference), we get a total estimated dose to Blood Forming Organs (BFOs) of approximately 35 cSv. This dose is within the recommended annual dose limit of 50 cSv, but for a yearlong stay, it would exceed it. If we increase the shielding thickness to 100 cm, we can reach a point estimate of BFO dose of about 2.7 cSv[22], and thus be more compliant with the allowable limits.

As far as long-range EVAs are concerned, we should account for storm shelters: they can be man-made, natural (e.g. lava tubes) or both, or they can be deployable in-situ during the excursions. The main factor is to make sure that each crewmember is within the optimal distance to a predefined storm shelter to reach it in time.

Finally, the base modules could be partially buried in lunar ground removing regolith from the ground to accommodate them, or using the regolith removed for ISRU operations. Moreover, the use of in-situ produced water as a shield is envisioned.

V. ISRU PLANTS

Once ISRU requirements and purposes are defined, we detail the possible ISRU plants architectures. During first sorties, small rovers will be deployed for geology scouting and site mapping in order to identify the most suitable location for a plant. While surveying, the topography of the Shackleton Crater rim shall be taken into account since a lot of factors influence the positioning of the ISRU plant. It shall be on an ilmenite rich area, close enough to cold traps to allow experiments and eventually the use of regenerative fuel cells without the need of cooling systems[23], far enough from the habitat to avoid dust contamination due to excavation activities, close to the spaceport for refueling purposes, but not in line with approach and take off trajectories.

After a site is found, a demo for the plant will be deployed. This plant is expected to have low yield and is powered by a demo nuclear plant. Once the technology is well assessed, a small plant and lately a big plant will be sent to fulfill the outpost's needs. All these plants have the same architecture, and use the same rovers to collect and transport regolith. These ISRU Utility Carts can excavate, collect, and transport regolith and raw materials.

Ilmenite Reduction Plant

As can be seen in Figure 5, an ilmenite reduction plant with a production rate of 20 mT of oxygen per year includes excavators to provide raw regolith, which will be transported to the plant where it can be either stored or directly processed. Once the regolith has been pre heated, its temperature rises up to 1050° C and the reaction takes place; metals are separated and water vapor is liquefied. Finally, water is electrolyzed and hydrogen and oxygen are produced and stored.

Considering the utility cart that we designed and estimates from literature[24], it is possible to obtain a first order sizing of the plant (Table 5). A safety factor of 30% has been adopted for spare vehicles.

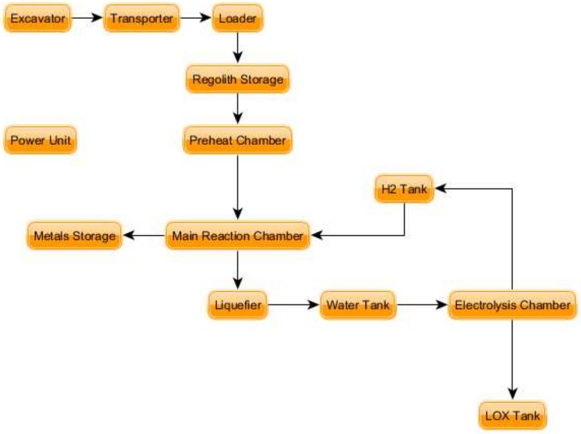


Fig. 5: Ilmenite reduction plant outline.

Element	Mass (mT)	Qt.
Excavator	0.97	2
Transporter	0.97	2
Loader	0.97	2
Spare Vehicles	1.75	1
Storage unit	2.62	1
Preheat chamber		1
Main reaction chamber		1
Metals storage		1
Liquefier-radiator	1.34	1
Water tank	0.67	1
Electrolysis chamber	1.08	1
H2 tank	1.01	1
LOX tank	0.58	1
Power generation unit	5.00	1
Total Plant Mass	19.87	

Table 5: First order sizing of ilmenite reduction plant.

Cold Traps Plant

As is shown in Figure 6, a cold traps plant with a 44 mT per year oxygen production rate includes excavators to provide raw regolith, which will be transported to the plant where it can be either stored or directly processed. Once the regolith has been dried and water and soil separated at a temperature of 50° C, water vapor is liquefied, water is electrolyzed and hydrogen and oxygen are produced and stored.

Considering the utility cart that we designed for the ilmenite reduction plant with minor modifications to account for soil, location, and temperatures differences with respect to the previous case, it is possible to obtain a first order sizing of the plant (Table 6). A safety factor of 30% has been adopted for spare vehicles.

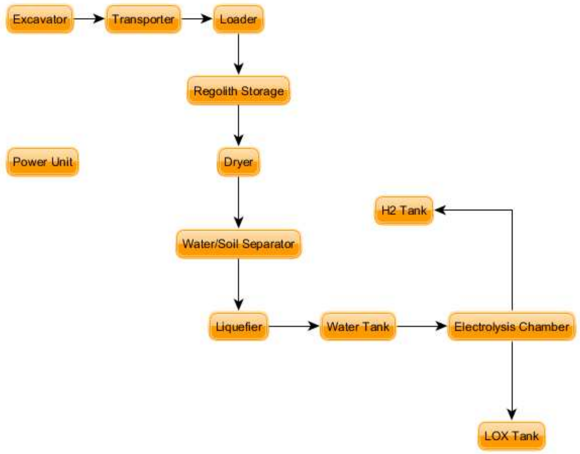


Fig. 6: Cold traps plant outline.

Element	Mass (mT)	Qt.
Excavator	1.21	2
Transporter	1.21	2
Loader	1.21	2
Spare Vehicles	2.18	1
Water-soil separator	0.80	1
Dryer	0.04	1
Liquefier-radiator	1.34	1
Water tank	1.14	1
Electrolysis chamber	1.08	1
H2 tank	1.71	1
LOX tank	0.98	1
Power generation unit	3.83	1
Total Plant Mass	20.38	

Table 6: First order sizing of cold traps plant.

VI. ISRU EVOLUTION

Although the architecture of the plants remains the same, the plants described in the previous section are the ones for a fully functioning outpost.

Now, it is needed to contextualize the ISRU into an incremental path towards the exploration of Mars. To obtain the final goal, a set of campaigns has been devised considering ilmenite reduction as the primary technology to be used, and cold traps as a possible and plausible development to explore other sources to extract oxygen.

Campaign 0

This campaign includes already planned orbital and robotic missions (e.g. Clementine, Lunar Prospector, LRO, LCROSS, Chang'e 3, SMART-1, Chandrayaan, GRAIL) and ISRU is not considered at this stage.

From now on, each campaign identifies a particular mission, or a set of particular missions. Consequently, each campaign has its own purpose (e.g. mission statement, mission objectives).

Campaign 1

This campaign is intended to enable robotic teleoperations to search for possible ISRU sites. If it exists, a crew shall be delivered for six months onto a cis-lunar station in 2022, followed by robotic assets on possible ISRU lunar sites. In any case, robotic assets shall be operated to locate iron-rich soils and establish topography of the lunar south pole.

One single mission is envisioned for this campaign, using an SLS 70 M.

Campaign 2

This campaign is intended to survey lunar south pole locations for possible resources and enable ISRU technologies testing. An ISRU demo to test oxygen production shall be delivered on the identified sites, together with two rovers to support feedstock collection and hauling, and to perform experiments on ice extraction. Moreover, an unpressurized manned rover for exploration can be deployed for future survey missions, when a crew will be delivered to conduct experiments. During this campaign, ISRU is not considered for ECLSS or propellant production, but only for validation.

All cargo assets deliveries to the Moon south pole are unmanned, while manned missions begin in 2026 and last 45 days, during which ISRU studies and exploration activities are performed. For these missions the Falcon 9 H is envisioned as launcher for unmanned missions and the SLS 70 M for manned. Three unmanned missions will deliver utility carts, unpressurized rovers, the ISRU demo, and a pressurized rover. Finally, one manned mission will deliver astronauts for a sortie.

Campaign 3

This campaign is intended to explore for further resources and enable a higher degree of ISRU. Once an ISRU plant is delivered on lunar surface, Initial Operational Capability can be reached with respect to the modules already emplaced. Then, a crew will be delivered on lunar surface to check ISRU plant operations (which are automated and autonomous) and efficiency, and continue studies on new ISRU technologies.

Unmanned missions begin in 2029 and deliver cargo assets to the Moon south pole including an ISRU small plant and a pressurized rover. Manned missions begin in 2029 and last 180 days; using delivered assets to perform ISRU and establish first long-term human presence: now ISRU is considered for producing ECLSS consumables (accounting for regeneration), but not for propellant production.

A first mission with SLS 100 and SLS 70 delivers the ISRU small plant, while a second mission with SLS 70 M delivers the crew.

Campaign 4

This campaign is intended to establish ISRU within a permanent outpost scenario, thus, it has to deliver an ISRU plant on lunar surface and allow in-situ production of oxygen as propellant and for life support considering two crew rotations per year. In this scenario, reentry vehicles relying only on in-situ produced propellants are envisioned.

A single mission using an SLS 130 is envisioned for delivering the 20 mT per year ISRU plant.

Campaign 4+

This campaign is intended to establish ISRU for Mars mission propellant production within a permanent outpost scenario, thus an ISRU plant on lunar surface has to be delivered to allow in-situ production of oxygen for ECLSS and as propellant, and eventually deliver it in an L1 depot. All of this will only be necessary if development in electric propulsion will not allow faster trips to Mars with respect to chemical systems.

A single mission using an SLS 130 is envisioned for delivering a cold traps ISRU plant, while at least two will be needed in case of expansion of the ilmenite reduction facility.

Figure 7 summarizes all the campaigns illustrated above, showing their disposition in time and the launches needed. The final goal is of course Mars.

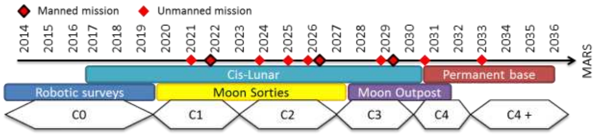
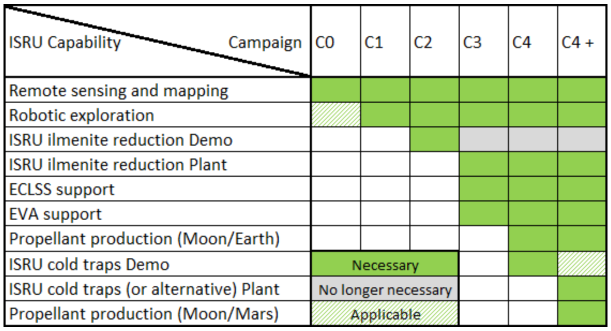


Fig. 7: Campaigns schedule.

To summarize the effort to be made concerning ISRU within the architecture described, we have gathered the ISRU capabilities and mapped them onto the campaigns described above. The result is shown in Figure 8, where it is possible to appreciate the incremental implementation of capabilities, as postulated in previous sections.



ISRU Capability \ Campaign	C0	C1	C2	C3	C4	C4 +
Remote sensing and mapping	🟩	🟩	🟩	🟩	🟩	🟩
Robotic exploration	▨	🟩	🟩	🟩	🟩	🟩
ISRU ilmenite reduction Demo			🟩	▒	▒	▒
ISRU ilmenite reduction Plant				🟩	🟩	🟩
ECLSS support				🟩	🟩	🟩
EVA support				🟩	🟩	🟩
Propellant production (Moon/Earth)					🟩	🟩
ISRU cold traps Demo	🟩 Necessary				🟩	▨
ISRU cold traps (or alternative) Plant	▒ No longer necessary					🟩
Propellant production (Moon/Mars)	▨ Applicable					🟩

Fig. 8: Incremental ISRU capabilities during the envisioned campaigns.

VII. CONCLUSION

A possible architecture for exploiting lunar resources on the long run has been presented. The incremental path here proposed is based on ilmenite reduction technology with cold traps exploitation as a possible alternative once we will have ground truth. However, other technologies to produce oxygen in-situ are currently under study[25] and will lead to new possibilities. The advantage of the architecture here outlined is that of being composed by elements with a suitable TRL to be adopted in the time frame proposed, thus making it more likely to be realized in the near future.

Possible developments of this study may include a more detailed (i.e. with higher resolution maps) illumination analysis of the Shackleton Crater rim to better identify a suitable site for solar arrays positioning and outpost layout definition. Moreover, as modules are designed and trajectories are optimized, the estimates for oxygen needs will be more precise, leading to a better definition of requirements. Finally, a thermal analysis and an integration study to understand how to combine ilmenite reduction plants with cold traps exploitation demos, will allow the concurrent functioning of both technologies for studying purposes, while reducing the IMLEO of the whole system.

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